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REMOVAL OF LIQUID FROM SOLUTION GAS STREAMS DIRECTED TO FLARE AND DEVELOPMENT OF A METHOD TO ESTABLISH THE RELATIONSHIP BETWEEN LIQUIDS AND FLARE COMBUSTION EFFICIENCY

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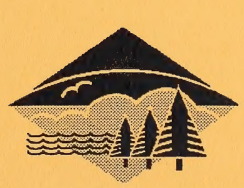

Removal of Liquid from Solution Gas Streams Directed to Flare and Development of a Method to Establish the Relationship between Liquids and Flare Combustion Efficiency

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EXECUTIVE SUMMARY

Solution gas flares at oilfield battery sites make up over 80% of the volume of gas flared in Alberta. The efficiency of these flares can be significantly reduced by the presence of liquid hydrocarbons in the gases being flared, resulting in emissions of unburned hydrocarbon compounds. These findings have stressed the importance of examining gas-liquid separation technologies, in relation to what is now being used and other separation technologies that may be available for use at oilfield battery operations. Improved liquid hydrocarbon clean-up of solution gas may produce significant improvements in flare combustion efficiency and reduction of flare emissions.

The current study was undertaken to examine technologies that could be used or developed to enable the upstream oil and gas industry to reduce the hydrocarbon emissions from the flaring of solution gas. The objectives were to examine and evaluate possible surrogate methods for monitoring flare performance, review gas/liquid separation technologies available for solution gas cleaning, examine the application of numerical simulation for improving separator design and develop a strategy for field testing of existing and improved solution gas cleaning technologies.

Combustion efficiency measurements by flare flame sampling are complex, time consuming and expensive. Potential surrogate methods to monitor flare performance include measuring the solution gas properties and/or remote monitoring of flare properties or emissions. Industrial equipment is available for continuously measuring flare gas flow rate (ultrasonic flow meters) and composition (gas chromatographs). Either isokinetic sampling techniques or in-line optical techniques can be used to measure the amount of entrained liquids. Single particle laser scattering optical instruments can also measure a droplet size distribution for increased information on separator performance. Both techniques have been used in field testing of industrial scale separators to lead to improvements in their design. However, neither isokinetic sampling nor laser scattering would be practical for continuous monitoring of solution gas liquids content.

Remote monitoring systems were also examined as an alternative to the present flame sampling methods of assessing flare efficiency. Many varieties of both laser and infrared spectrometer systems have previously been examined by other researchers for the measurement of hydrocarbon emissions, including fugitive emissions from petroleum operations, for petroleum exploration, and for examining exhaust emissions from vehicles. Some of the methods have shown promise for their particular application, while others were not as accurate as expected when compared to results obtained by more traditional chemical analyses (i.e. gas chromatographs). There has been one know attempt to quantify flare emissions by a remote measurement technique. The passive infrared system used in this application had considerable difficulty in the detection of hydrocarbon species. There are currently no proven techniques for remote monitoring of flare performance.

Literature and Internet searches were used to examine available techniques for the separation of liquid hydrocarbons from gasses. The majority of equipment used in the oil industry generally use one or more of either gravity, centrifugal, or impaction type separators. Separator selection and sizing is always a trade off between equipment size and cost and separation efficiency. If a separator is under-sized for the gas flow and/or liquid loading or operated outside the design parameters, high liquids carry over can occur leading to poor flare performance. This may be due to inadequate residence time for good gravity separation or due to re-entrainment of liquids in the mesh pad or vane separator (if present). Operating the separator with excessive level of collected liquids will also reduce the gas residence time and increase liquids carry over.

Gas-liquid separators, including mesh pads and coalescing filters, will only remove liquid droplets. Light oils present in the vapour phase at the exit of the separator may condense out to form entrained liquids if the flare gas temperature drops between the separator outlet and the flare tip. This cooling and condensation may be a significant source of entrained liquids, even at a site with efficient separation equipment installed. No specific data was found in the literature reporting direct measurement of the performance of typical gas-oil separators installed at oilfield battery sites in Alberta.

The application of Computational Fluid Dynamics (CFD) to the design and understanding of flows in various types of separators is a well established and practical method of helping to design separators for particular applications. Numerous examples of the use of CFD to evaluate separation devices relevant to oil field applications have been documented in the literature. CFD can be used to visualise and understand the details of the internal flow patterns in the separation device. The engineer can use this understanding to improve separation efficiency, reduce pressure drop and increase the capacity of various design or retrofits. These applications would be of great help for use in examining and designing separator systems used in oilfield battery operations for the more effective removal of liquid hydrocarbons from solution gas.

Based on the information that has been gathered for this study, a strategy for testing of separation technologies and technologies that could be used as surrogates for flare combustion efficiency measurements was developed. The proposed program recommends the development of a field test facility that would allow testing of available equipment that could be used to reduce impacts of flare emissions. This includes the examination of the impact of entrained liquids on flare emissions, the testing and/or development of improved entrained liquids recovery techniques, and the development of testing methods for monitoring flare performance either directly or by surrogate methods.

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Removal of Liquid from Solution Gas Streams Directed to Flare and Development of a Method to Establish the Relationship between Liquids and Flare Combustion Efficiency

1.0 BACKGROUND

Solution gas flares make up over 80% of the volume of the gas flared in Alberta. Emissions from flares typical of those found at oilfield battery sites in Alberta have been found to contain large numbers of hydrocarbon compounds that were produced by pyrolytic reactions within these flames. Liquid hydrocarbon fuels or condensates co-flowing with the gas streams produced the greatest effect on impairing the ability of the resulting flame to destroy the pyrolytically produced hydrocarbons as well as the original hydrocarbon fuels directed to the flare. Crosswinds were also found to reduce the combustion efficiency of the co-flowing gas/condensate flames by causing more unburned fuel and produced hydrocarbons to escape into the environment. Entrained liquids going to flare also represent lost product due to ineffective design or operation of the separations equipment installed to recover these liquids.

Previous work (Strosher, 1996) both at the pilot scale and field studies at oilfield battery sites showed that:

- pure methane or propane gas streams burned at greater than 98% combustion efficiency in lab and pilot scale tests
- the addition of liquid hydrocarbons or condensates reduced combustion efficiency and increased both the amounts of unburned fuel and hydrocarbons produced in the flame (30% heptane in natural gas reduced the combustion efficiency to approximately 80%).
- the emissions from flaring sweet solution gas increased with increased liquids content, as indicated by level in the liquids knockout drum (the amount of entrained liquids was not measured).

The field tests with varying oil level in the knock out drum best demonstrated the importance of liquids content on flare emissions. Reducing the liquids level in the knock out drum reduced measured hydrocarbon by 25% and carbon particles by 40% resulting in a flare combustion efficiency increase of 6 to 7%. Thus the improved separation and recovery of hydrocarbon liquids from solution gas going to flare may be one of the most economical and effective means of reducing emissions of unburned hydrocarbons. The measurement of liquid content of gas going to flare may also be a good surrogate for direct measurement of flare emissions.

In light of these findings, the removal of liquid hydrocarbons from solution gas being directed to flare may provide the most cost-effective means of increasing flare combustion efficiencies and reducing flare emissions of deleterious hydrocarbons. An evaluation of liquid hydrocarbon separation technologies was therefore required.

2.0 OBJECTIVES

The objective of this study was to examine the best possible technologies that could be developed to enable the upstream oil and gas industry to substantially reduce hydrocarbon emissions from the flaring of solution gas at oilfield battery sites in Alberta. These investigations were designed with specific objectives to:

1. Examine and assess technologies that can be used as surrogates for combustion efficiency measurements;
2. Search current literature and available technologies for liquid/gas separation techniques that could be used, modified or developed for solution gas clean-up;
3. Assess and evaluate these technologies in relation to efficiency and economics, using numerical simulations via computational fluid dynamic (CFD) software when possible;
4. Develop strategies and a program for testing of the most practicable separation technologies and methods that can be used as surrogates for flare combustion efficiency; and
5. Construct components of a protocol system for the removal of liquids from solution gas streams, and/or conduct some preliminary testing.

The following report summarizes the results of this project for each of the five objectives.

3.0 SURROGATES FOR FLARE COMBUSTION EFFICIENCY MEASUREMENTS

Combustion efficiency measurements of flare emissions by present means are very complex, time consuming, and expensive to conduct. One of the tasks of this study was to evaluate methods and techniques that could act as a surrogate for the measurement of combustion efficiency. Systems that were examined for this study included either in-line systems of measurement for the hydrocarbon components that are known to reduce combustion efficiency or an external remote measurement system for hydrocarbons and combustion products in the flare

emissions. These systems were only evaluated on the basis of their possible application as a surrogate means to the flare testing. Further evaluation would be required, including eventual testing of these systems in conjunction with analytical measurements, as performed in previous investigations, to validate their applicability.

Surrogate technologies examined, included both liquid droplet or vapor phase liquid hydrocarbons measurement as well as methods for measuring combustion products in the emissions by remote techniques. The following is a review of the findings for both methods.

3.1 Measurement of Flare Gas Composition, Flow Rate and Entrained Liquids

The chemical composition and content of entrained liquids will be one of the factors that have an impact on flare combustion efficiency and emissions. A direct correlation between inlet gas composition and absolute flare performance is likely not possible because of the large number of other factors, such as flare tip design, crosswinds, etc., that also effect flare performance. However, initial field measurements by Strosher (1996) suggest a strong correlation between entrained liquids content and flare combustion efficiency and emissions for a given flare at a given site. On-line measurement of flare gas flow rate, composition and content of entrained liquids may be a good surrogate measurement of relative flare performance or act as an indicator of upset conditions.

A literature survey and Internet search was performed to find instrumentation and measurement techniques for flare gas flow rate, composition and entrained liquids content. Both on-line continuous and intermittent measurements were considered.

3.1.1 Flow Rate Measurement

Ultrasonic instruments would likely be the preferred method for measuring flare gas flow rate. With ultrasonic instruments, there are no obstructions in the flow and no pressure drop caused by the sensing element. Several manufacturers make ultrasonic flow meters. Panametrics Model 7168 flowmeter is specifically marketed for measuring flare gas flow rate with an ultrasonic

transit-time technique. Other instrumentation that may be suitable for measuring flow rate include orifice plate meters, vortex meters, venturi meters, etc. Each of these instruments have they advantages and disadvantages for the flare application.

3.1.2 Gas Composition Measurement

Monitoring changes in the flare gas composition may provide a surrogate indication of poor flare performance. Experiments in laboratory and pilot scale flares (Strosher, 1996) indicated that the addition of light hydrocarbons, particularly aromatic hydrocarbons, reduced the flare combustion efficiency and increased the amount of hydrocarbon emissions. This occurred even though the compounds were in the vapour phase in the flare gas.

The Panametrics ultrasonic flow meter can give an indication of changes in the gas phase molecular weight by analyzing changes in the speed of sound in the flare gas. This calculation makes assumptions about the composition of the flare gas. In particular, the calculation has to be adjusted for the nitrogen content of the gas being analyzed. The molecular weight measurement is not effected by changes in entrained liquids content.

Gas chromatography is the standard method in the laboratory to analyze the composition of gas samples. Several models are also available for industrial use. With recent advances in electronics and miniaturization, rugged and compact gas chromatographs have become available that are capable of analyzing flare gases containing vapour phase hydrocarbons up to C5. Along with miniaturization, the sample analysis time has been reduced to less than five minutes in most cases. Microsensor Technology Inc. is one company that sells this type of gas chromatograph, including models specifically for analyzing natural gas. The hydrocarbons present in the gas phase will vary with temperature. With a heated isokinetic sampling system hot enough to vapourize any entrained hydrocarbons and with a heated injection gas chromatograph, this analysis technique could yield a total composition for the flare gas. Knowing the temperature and pressure of the flare gas, vapour pressure calculations could then be used to estimate the concentration of entrained liquids in the flare gas stream.

3.1.3 Entrained Liquids Measurement

Experiments to date indicate that entrained hydrocarbon liquids significantly decrease flare combustion efficiency and increase emissions of unburned hydrocarbons and soot. Entrained liquids going to flare also represent lost revenue from hydrocarbon liquids that could have been recovered. On-line measurement of the concentration and preferably also the droplet size distribution would yield valuable data on solution gas separator performance and give an indication of potential high flare emissions.

The scientific and patent literature were reviewed to identify instrumentation and methods for on-line or intermittent measurements of entrained liquids amount and droplet size distribution. For a surrogate measurement of flare performance, the total amount of entrained liquids is most important. For the measurement of solution gas separator performance, an instrument which also measures droplet size distribution would give the most useful information.

Methods for entrained liquids measurement were either sampling techniques or optical techniques. To determine entrained liquids by sampling, an isokinetic probe is used to withdraw a representative sample of gas at a measured flow rate for a measured time. The gas passes through a series of filters to collect the entrained liquids. The amount of liquids is determined by the weight gain of the filters and sampling train. Cascade impactors can be used to measure droplet size distribution, assuming that the droplets do not coalesce or evaporate in the sampling train. Optical techniques require the gas containing entrained liquids to flow through a measurement cell or focal volume of an optical cell. For droplet diameters below about 100 um, either imaging, laser diffraction or light scattering techniques are used to determine particle concentration and, in some instruments, droplet size distribution. Table 1 describes some of the advantages and disadvantages of the instruments for measuring entrained liquids.

Table 1: Instruments for Measuring Entrained Liquids

Method	Advantages	Disadvantages
extractive sampling and filtering	- relatively inexpensive - liquids sample collected - minimal calibration needed	- liquids may coalesce, condense or evaporate in the sample train - labour intensive technique - not appropriate for continuous monitoring - difficult to obtain size distribution - sampling gas velocity can bias the particle size distribution
imaging techniques	- no sampling train to disturb the flow - medium cost	- cannot measure droplets < 5um - need to analyze photos with image analysis software - not suitable for on-line measurements - need clean optical access
laser diffraction	- measure drops 0.5 to 1000 um - no sampling train to disturb the flow - may be suitable for continuous monitoring	- medium cost - need clean optical access - some instruments do not give particle size information
single particle laser scattering	- measures drops 0.2 to 200 um - no sampling train to disturb the flow - may be suitable for continuous monitoring - measures concentration, droplet velocity and size distribution	- particle concentration must be below 10^7 particles/cm^3 - less rugged instrument - high cost - need clean optical access

Fewel et al., 1997 measured the performance of gas-liquid separators as part of a program to improve their efficiency. The study used a combination of extraction sampling to measure the total concentration of entrained liquids and laser single particle scattering to measure a particle size distribution. For accurate measurement of liquids content, the isokinetic sample probe position was varied over the pipe cross section to get a representative sample. The sampled gas was filtered with 0.1 micron filters to collect all entrained liquids.

The measurement of entrained droplet size distribution has been used extensively in the study of two-phase flow (e.g. Azzopardi et al., 1991). In this study, a Malvern Instruments diffraction

instrument was used to measure a droplet size distribution, assuming a Rosin-Rammler size distribution. Two-phase flow in a pipe can contain a significant amount of liquid flowing as a film on the pipe. The film flow rate was measured by drawing about 2% of the gas flow through a porous wall section, separating the phases and measuring the amount of liquid. The amount of the total liquid flow (film plus entrained drops) that was entrained as drops varied from 10 to 50% with variation in gas flow rate and gas to liquid flow ratio.

None of the instruments or sampling techniques currently available for measuring entrained liquids in a gas flow would be rugged or economical enough for continuously monitoring of a flare gas flow. Isokinetic sampling combined with single particle laser scattering is required for accurate measurement of both the amount of entrained liquid and the droplet size distribution.

3.2 Remote measurement of combustion products

Another way of examining flare efficiency and the associated products of combustion is by using an alternate but simpler method of characterizing the flare emissions themselves. It has long been thought that optical sensing techniques could be developed to remotely measure at least the most important and/or major constituents of this combustion process with enough accuracy that could then be used to evaluate flare efficiencies in a more economical way. The current methods that have been used, including probe sampling along with the associated analytical techniques required to characterize the entire emissions is a very tedious, time consuming, and expensive method to evaluate the efficiency of flares. It is, however, the only method to date that has provided a relatively accurate means to provide these assessments, and thus should be used to help in developing and addressing the remote optical measurement methods.

Remote sensing methods are reliant on the fact that the emission products used in efficiency calculations are optically active. Each species has to have its own radiant emission (signature) in the region of the spectrum. These signatures, when related to concentrations of sufficient products of the radiant emissions from combustion, are how the optical spectroscopy methods could be used to examine flare efficiencies both remotely and non-obtrusively. Remote optical measurements are considered more global by their measurement in-so-far as spatial averaging is

being obtained. By comparison, probe methods are considered more point source except when time averaging (sample integration over longer periods of time) is used. The following is a partial list of some of the optical (Lidar- light detection and ranging) techniques that could be considered for the remote measurement evaluations.

Some Potential Remote Measurement Techniques

1. Differential Absorption Lidar (DIAL) uses light at two or more wavelengths, backscattered by atmospheric aerosols, to generate self-calibrated, range-resolved measurements of the concentration of various gas species along an extended path. DIAL systems may be used to map chemical vapor clouds over ranges of several kilometers.

2. Backscatter Lidar is useful for identifying the presence and spatial distribution of aerosols over ranges of tens of kilometers with resolutions of several meters.

3. Differential Scatter Lidar uses two or more transmitted wavelengths to detect the presence and identify the composition of atmospheric aerosols. The DISC technique makes use of the fact that the aerosol backscatter cross section is a function of the aerosol material as well as the particle shape and size distribution.

4. Ultraviolent Fluorescence is used to detect chemical species that emit a characteristic flourescence spectrum when excited with UV light (primarily aromatic hydrocarbons). This technique may also be used to detect biological aerosols by virtue of the fluorescence of aromatic amino acids in the bacterial cell wall.

5. Raman Scattering is an inelastic scattering process used primarily in the UV and visible spectral regions to detect and identify molecular species. The scattered light is generally downshifted in frequency or wavelength by the characteristic rotational/vibrational energies of the scattering molecule, and serves as a molecular fingerprint.

6. Absorption Spectroscopy is used to obtain path-integrated concentrations of atomic and molecular species by virtue of the absorption of light at wavelengths characteristic of quantum-mechanically allowed transitions.

7. Fourier Transform Infared Spectroscopy (FTIR) is a method of absorption spectroscopy performed in the infrared spectral region that utilizes an interferogram obtained using a scanning Michealson interferometer. The interferogram is Fourier transformed to obtain the absorption spectrum. The FTIR systems can operate in both active and passive modes.

8. Frequency Modulation Spectroscopy is a high-sensitivity absorption technique usually implemented with tunable continuous wave laser sources, such as diode lasers. It is useful for measuring path-integrated concentrations of trace gases at sub-parts-per-billion levels.

According to SRI International, many environmental, military, and industrial problems are amenable to solution with the help of both point and remote optical sensing systems. The following list of their recent applications illustrates how the wide variety of techniques and instruments can be applied to solve many of these problems.

- DIAL lidar has been used to quantifiy emissions and concentrations of greenhouse-effect gases in the atmosphere.
- Airborne and ground-based backscatter lidar systems have been used to study the detailed behavior of smokestack plumes, and to detect and characterize non-visible high altitude cloud layers.
- Infared DIAL systems have been used to map clouds of chemical warfare agent stimulants in the atmosphere for military applications.
- The FMS systems have been used to detect trace gases in the atmosphere that play key roles in photochemical processes, to detect impurities in gases used for industrial processing, to measure carbon isotope ratios on human breath for medical diagnosis, and to detect the presence of concealed explosives for airport security applications.
- Ultraviolet fluorescence has been used to detect biological warfare simulants in the atmosphere using both remote and point sensing systems.
- Passive FTIR systems have been used from airborne platforms to measure chemical pollution over wide areas.
- Frequency-agile lidar (FAL) systems have been used to detect both chemical warfare simulant vapors and volatile and toxic organic compounds in the atmosphere.

One of the remote monitoring systems currently being developed and used by Laser Exploration Inc. is focused to measuring hydrocarbon trace gas concentrations in the atmosphere over a subsurface reservoir of petroleum deposits for exploration purposes. The Lidar System they are using is based on a unique laser capable of emitting high power optical (light) pulses in the 2 to 5 μm spectral (wavelength) region. The 2 to 5 μm spectral region is significant for two reasons. First, gaseous hydrocarbons have been determined to be optically absorptive within this region. That is, they produce a measurable, quantifiable "signature" in this optical band which can be used to identify specific hydrocarbon gas species. Second, the atmosphere is optically transparent in the 2 to 5 μm spectral region. Consequently, this region offers the opportunity for optical remote sensing. Specifically, hydrocarbon trace gas concentrations can be measured over significant distances from the laser source itself.

The selected laser source in this case is the solid state laser material Cr3+:LiSrAlF6 (also denoted Cr:LiSAF). Cr:LiSAF lasers were pioneered by the Lawrence Livermore National

Laboratory, Livermore CA (Chase et. al., 1989). Previous Cr:LiSAF lidar systems have been developed by the Los Alamos National Laboratory, Los Alamos NM (Early et. al., 1995).

In the development of this measurement system, it was determined that by using Stimulated Raman Scattering to optically shift the laser wavelength from the near infrared to the mid-infrared, termed Raman Shifting, several important advantages for lidar applications were obtained. The Raman shifting allows a spectrally-narrow laser to be tuned to very specific hydrocarbon absorption features which significantly improves the lidar system accuracy for determining very minute trace gas concentrations and enables the lidar to identify and classify specific hydrocarbon species. Other laser technologies capable of producing sufficient 2 to 5 μm light for long-range open path lidar applications, such as Optical Parametric Oscillators (OPOs) and lead salt diode lasers, do not produce spectrally-narrow laser light. Thus, these techniques cannot achieve the level of concentration-measurement precision achievable with a Raman Shifted Cr:LiSAF lidar. The spectrally- narrow Raman Shifted lidar was the superior spectroscopic source, enabling both an improved hydrocarbon trace gas concentration measurement and the rejection of competing background gaseous species.

Another major advantage of a Raman Shifted Cr:LiSAF lidar is the speed at which the laser can be tuned between spectral features of interest. The Raman Shifted lidar can be tuned to different absorption features on an optical shot-by-shot basis. OPOs and lead salt lasers must be tuned more slowly and generally over much longer wavelengths due to their significant spectral-bandwidth of the emitted light. Laser tuning speed is important due to the dynamics within the environment itself. If each laser shot encounters a sufficiently-different atmosphere (in terms of dust loading, wind, turbulence, etc.), then the lidar measurement accuracy is severely compromised. Atmospheric and reflector variability will likely be the limiting factors in the capabilities of all OPO and lead salt laser based lidar systems. With the Raman Shifted Cr:LiSAF lidar, however, very rapid pulse emissions are possible. OPHIR has already demonstrated in the laboratory environment that two laser pulses can be emitted within the envelope of one laser flashlamp pulse, roughly 60 μs apart. The atmosphere is quite stable on this time scale and Differential Absorption Lidar (DIAL) measurements can be obtained with exceptional quality and precision.

Another widely used technique for remote optical measurement of hydrocarbons and other gases is Fourier Transform Infrared (FTIR) spectroscopy. A pulsed-molecular-beam Fabry-Perot cavity Fourier-transform microwave spectrometer developed at NIST demonstrated sensitivities for many polar gas-phase molecular species in the low parts per million (ppm) to parts per billion (ppb) range (Lovas et. al., 1995). The highest sensitivity was obtained using neon or argon carrier gas but nitrogen or air could also be used, with some loss in sensitivity (up to 100 times) due to the less efficient rotational and vibrational cooling in the molecular beam with diatomic gases.

Gibbs et. al. (1995), found that spectroscopic techniques in the infrared and ultraviolet spectral regions could efficiently meet increasing measurement challenges in real-time detection of vehicle emissions in urban air quality studies. A Fourier transform infrared (FT-IR) spectrometer was used to continuously monitor motor vehicle exhaust emissions. The FT-IR identified several exhaust components, including ethylene, acetylene, propylene, isobutylene, the hydrocarbon continuum, carbon monoxide, carbon dioxide, methane, nitric oxide, and nitrous oxide. In 1993, the US-EPA had also suggested the use of these remote sensing devices as a supplemental tool for Vehicle Emission Control (EPA 400-F-92-017). Remote sensing systems for this purpose, have been developed by Remote Sensing Technologies of Denver and the Santa Barbara Research Centre (a subsidiary of Hughes Electronics). They are primarily designed to measure carbon dioxide, carbon monoxide, hydrocarbons, and occasionally nitrogen oxide emissions. Accuracy for the carbon monoxide measurements was found to be within +/- 5% while hydrocarbon accuracy was +/- 15%.

Field studies were used to evaluate the strengths and limitations of open-path FTIR for the measurement of volatile organic compounds within operating process units of petroleum processing facilities (David et al, 1995). Gas chromatographic-based measurements were made in parallel with the infrared measurements to provide a verification on the accuracy of the infrared results. Measurements by GC at plants found extremely low (sub-ppm) concentrations of organic compounds within the units tested. FTIR results were generally lower than those observed by the three GC methods. They concluded that the open-path FTIR measurements

appeared to suffer from a number of limitations, including problems with background correction, high detection limits and the impact of meteorological conditions. Further refinements in the technology were recommended.

Very little research has been carried out using remote measurement techniques in relation to flare emissions. Persky and Spellicy, 1984, examined one such technique to determine how readily and accurately it could be used as a measure of flare efficiency. In this study, passive infrared methods were evaluated to remotely monitor the efficiency of industrial flares. Exhaust products were examined from a small scale industrial flare under a wide range of operating conditions, at several positions in and above the combustion zone. They concluded that the most serious uncertainties of these methods were in the spatial distributions of temperature and gas concentration, and in the detectability of hydrocarbon species.

4.0 CURRENT LITERATURE AND TECHNOLOGIES FOR SEPARATION AND RECOVERY OF LIQUIDS FROM GAS STREAMS

There are four basic mechanisms that can contribute to separating a liquid phase from a gas phase (Jacobs and Penny, 1987). These are:

- gravity
- centrifugal force
- impaction (or interception)
- electromotive force

Gas-liquid separation is an issue in several major industries, including steam generation, pollution control and petrochemicals. As a result, there is a wide variety of equipment commercially available for separating liquids from gas streams, as evidenced by several pages of listing in the Thomas Registry. Designs available include gravity separators, cyclones, vane and mesh-type mist eliminators and coalescing filters. Several designs combine features of several of these separator types. Some of the designs and techniques developed in other industries may be applicable in oil field separation if they are rugged enough.

Separation equipment used in the oil industry generally use one or more of the first three mechanisms. Electrostatic precipitators, which are usually applied for the separation of fine solids (<50 μm) from a gas stream, use the fourth mechanism. For gas-liquid separation, the mechanisms are listed in order of increasing ability to remove fine droplets. Figure 1 shows the range of liquid droplet size for some example flows and the range of droplet removal for different styles of separators.

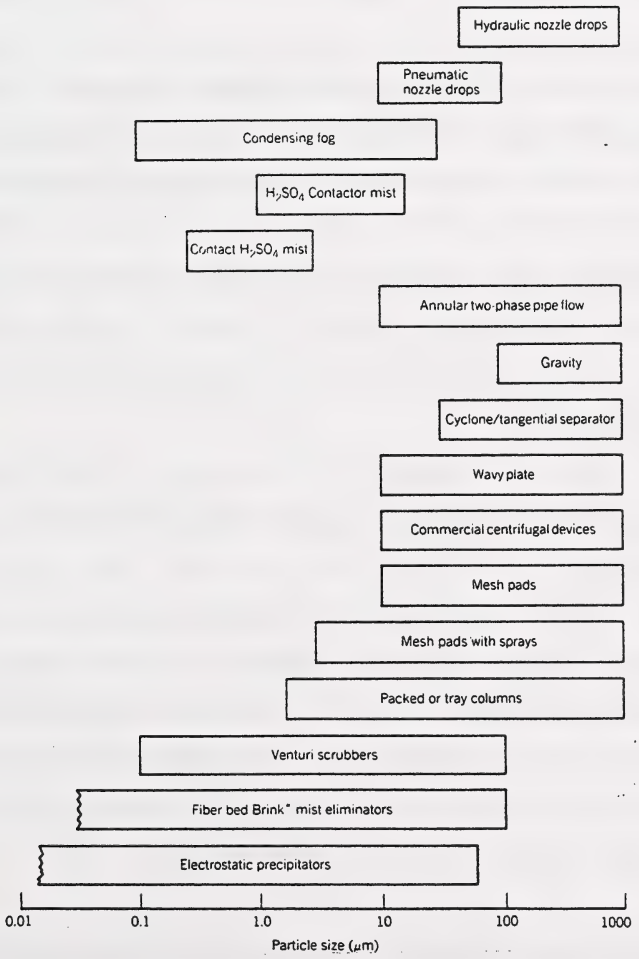

Figure 1: Typical Liquid Droplet Sizes and Vapour-Liquid Separator Application Range (from Jacobs and Penney, 1987)

4.1 Gravity Separators

Gravity separators depend on the density difference between the solids, oil droplets and gas. The residence time required in the gravity separator for the liquid drops to settle depends on the droplet size, density difference and gas flow patterns in the separator. Several handbooks contain correlations for calculating the particle terminal velocity and estimating the vessel size required for good separation. As relatively long residence times are needed for gravity separation, any separator design will be a tradeoff between vessel size and liquids recovery.

Typical gravity separators will only remove liquid droplets above about 150 μm. Baffles are often placed in gravity separators to increase liquid removal. If gas velocities are too high in the vicinity of the baffles, excessive liquid re-entrainment will occur. The typical gravity separator also acts as a storage tank for the recovered liquids. The gas velocity will change with liquid level in the tank, resulting in a change in the separation efficiency and outlet drop size distribution.

4.2 Centrifugal Separators

Centrifugal separators or cyclones use the density difference between the gas and liquid combined with centrifugal force to enhance gravity separation. This can significantly reduce vessel size and gas residence. Several commercial designs are available, but all are similar in that they direct the inlet flow into a centrifugal motion that causes the heavier liquid drops to contact a surface, coalesce and drain to a collector. The separation efficiency increases with inlet gas velocity up to a gas velocity of 80-120 ft/s. With further increase in gas velocities, the separation efficiency decreases due to liquid re-entrainment. For high gas velocities, the cyclone internals must be carefully designed to minimize re-entrainment.

Cyclone separation performance decreases with increasing vessel diameter. For large gas flow rates, multiple units will give better performance than a single large cyclone. The need for high gas velocities may result in a relatively high pressure drop and a narrow range of gas flow rates with good separation. Cyclones can generally remove liquids down to about 10 um in size.

4.3 Impingement Separators

These separators generally fall into either a mesh type or a vane type impact separator. Both types place an obstruction in the flow that causes a rapid change in the gas flow direction. Entrained liquids, having greater momentum than the gas, impact on the surface of the obstruction, coalesce and drain to a collector.

Vane type separators consist of parallel "wavy" plates spaced from a fraction of an inch to several inches apart. The shape of the plates force several direction changes in the flow with liquid particles coalescing on the plates and draining to a receiver. Separation efficiencies of 90% are possible for particles down to about 10 um.

Mesh type separators use a closely-knit metal or fiber-pad usually about 6 inches thick. Wire diameters vary from 0.006 to 0.15 inches. Liquid drops impact with the wire, coalesce and drain down the mesh pad. Mesh pad separators will remove droplets down to 10 um.

Both the mesh and vane type separators have an optimum gas velocity for good separation efficiency. If gas velocities are too high, liquids will re-entrain in the flow.

Coalescing filters use tightly packed fiber elements to give a combination of impingement and separation by Brownian motion for removal of droplets < 10 um. The large liquid drops impact with the filter element while the small drops diffuse to the fiber. These filters can separate very fine droplets (< 1 um) but at the expense of high-pressure drop and increased risk of plugging.

4.4 Scrubbers

Scrubbers use the impaction mechanism to remove entrained liquids. In this style of separator, liquid is sprayed into the gas stream, preferably with a drop size from 200 – 800 um range. These relatively large droplets collide with the finer entrained liquids, coalesce and are removed in a downstream separator suitable for large droplets (e.g. gravity separator, cyclone or vane

separator). Liquid scrubbers can also tolerate some solids without plugging. Spray towers can remove particles down to about 10 um while the venturi type scrubber can remove down to < 1 um.

4.5 Electrostatic Precipitators

Electrostatic precipitators are typically used to separate solids but will also separate liquids down to a particle size of less than 1 um. A dc voltage of 25 to 100 kV is used to create a corona discharge around the negative electrode. Particles in the flow are charged and attracted to the collector plate electrode where they coalesce and drain. Gas velocities must be kept in the range of 2 to 8 ft/s. Both the high capital cost and the risk of ignition would make electrostatic precipitators impractical for solution gas clean up.

4.6 Separators Typically used to Treat Solution Gas

Solution gas will contain a wide range of liquid droplet sizes, including the possibility of slugs of liquid. Annular two phase flow in a pipe can have droplet sizes up to 2,000 um. For pipe flow with a liquid wall film and a mist, the median diameter of the entrained droplets decreases with increasing gas velocity and decreasing liquid flow rate. In experiments of liquid aerosol flow in a pipe, Azzopardi et al. (1991) measured the droplet size distribution of the entrained water in air using a laser diffraction technique. The measured Sauter mean diameter of the entrained droplets increased from 36 to 100 um as the gas velocity decreased and the liquid loading increased. Droplets formed by vapour condensation can be much smaller, ranging in size from 0.1 to 30 um (Talavera, 1990).

The GPSA Engineering Data Book and the Petroleum Engineering Handbook include a technology review and design guidelines for separation equipment typically used in the oil and gas industry to separate gas and liquid streams. Oil field separation equipment is designed to be robust equipment and to handle a wide range of flow rates, changes in liquid content and surges in the flow. The separation equipment recommended in the handbooks rely primarily on gravity settling of the liquid droplets entrained in the gas flow. These gravity separation tanks may or

may not include a mesh or vane mist eliminator to remove liquid droplets less than 150 um. Some oil field separator designs also include centrifugal elements to aid in liquids separation and to reduce the size of the gravity separation tank.

The two broad designs of gravity separators used are vertical and horizontal. Vertical separators are used when the gas-liquid ratio is high or the total gas volumes are low. Liquid level control is not as critical since the amount of liquid in the vessel can fluctuate several inches without affecting performance. The liquid level in the vessel responds quickly to extra liquid in the gas stream, which could trigger a safety alarm. As well, vertical separators occupy relatively small areas of plot space.

Horizontal separators are used when large volumes of liquids and/or large volumes of entrained gas in the liquid are present. The larger liquid surface area in the horizontal separator and the long retention time of the liquids promotes the release of entrained gases. Horizontal separators can handle foaming liquids easier than vertical separators. There is also the possibility of creating three-phase horizontal separators to separate water and liquid hydrocarbons from the gas stream. Basic horizontal and vertical separators are shown in Figure 2.

4.6.1 Separators without Mist Extractors

Horizontal separators are the most common vessels that utilize gravity as the sole force used to separate liquids from gases. The inlet stream is slowed to a terminal velocity that allows the liquid droplets to fall out of the gas phase. To design a vessel without a mist extractor, the minimum size of the droplets to be removed must be set. This diameter is usually in the range of 150 to 2,000 microns. The length of the separator can then be calculated by assuming that the time required for the gas phase to flow from the inlet to the outlet equals the time for a liquid droplet of specified minimum diameter to fall from the top of the vessel to the liquid surface. These calculations are given in GPSA and Petroleum Engineering handbooks, and they are relatively simple to apply.

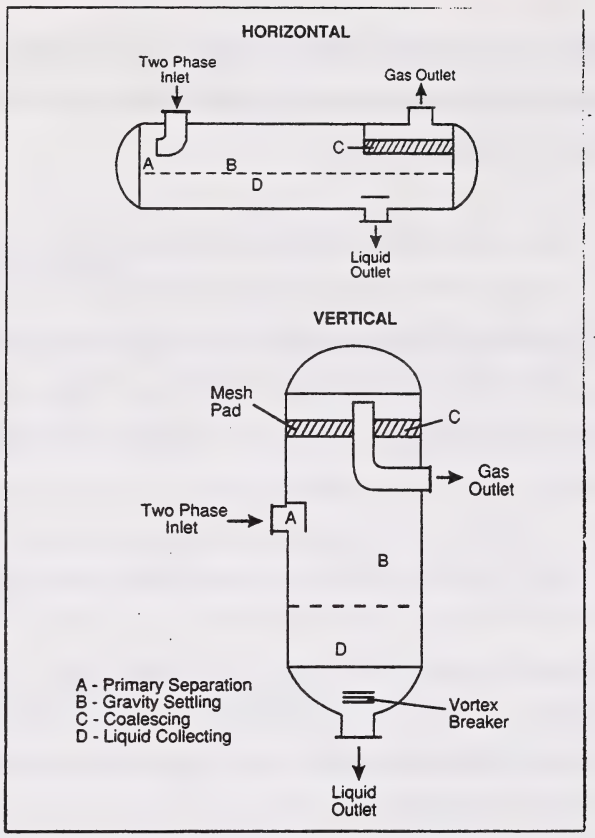

Figure 2: Example Vertical and Horizontal Separators

4.6.2 Separators with Wire Mesh Mist Extractors

Coalescing wire mesh pads can be used for the removal of droplets down to a size of 10 microns in diameter. The pad should be oriented horizontally, regardless of the vessel's orientation. The pad's performance degrades when it is tilted more than 30 degrees from horizontal. These pads are efficient only when the gas stream velocity is within the design specification. If gas velocities are too high, re-entrainment of the coalesced droplets will occur. Most installations use a six-inch thick pad with a nine to twelve pounds per cubic foot bulk density. The pressure drop across mesh pads usually does not exceed one inch of water, so it is considered negligible

for most applications. Mesh pads are usually avoided if fouling or hydrate formation is possible, since sludge or dirt build-up can cause the pad to be dislodged or cause a high pressure drop.

4.6.3 Separators with Vane Type Mist Extractors

Vanes are similar to wire mesh in that they coalesce liquids entrained in gas streams. However, vanes direct the coalesced droplets to a downcomer, which drops the liquid to the bottom of the vessel, rather than letting the drops fall through the flowing gas. The inlet flow of gas is directed through a vane, which forces the stream through a tortuous path. Vanes can be corrugated sheets of metal, which collect the liquid in the flowing gas by means of inertial differences between the heavier liquid and the lighter gas. The liquid is forced against the sides of the vane, promoting coalescing. Vanes generally achieve the same separation as wire mesh, but they do not plug and they can be contained in smaller vessels. Due to the many styles and sizes available, sizing and selection of a vane separator is done in consultation with the manufacturer. The GPSA data book does not include design equations for vane separators.

4.6.4 Separators with Centrifugal Elements

Centrifugal separators, or cyclone separators, can be used when solids as well as liquids are to be removed from a gas stream. They tend to require maintenance less frequently than filter separators. However, the efficiency is worse than many other types of separators. The pressure drop across the centrifugal elements is higher than that of vanes or wire mesh, and their operating flow range for highest efficiency is relatively narrow. The design of centrifugal separators is difficult without detailed knowledge of the vessel's specific internals, so manufacturers should be consulted when undertaking such a task. The GPSA data book does not include any design equations for cyclone separators.

4.7 Filter Separators

Filter separators can also remove solids and liquids from a gas stream, but with a higher efficiency than centrifugal separators. The solids are captured in the filter and the small liquid

droplets are coalesced into larger drops. A final mist extractor removes these larger drops. However, the filter elements must be replaced periodically because of fouling due to solids extraction. The filter is most commonly composed of a tubular fiber glass pack. The pressure drop of a clean filter is normally 1-2 psi, and they should be replaced or cleaned when the pressure drop exceeds 10 psi. For inlet streams with heavy liquid loads or free liquids, a horizontal separator with a liquid sump is commonly used. The liquid sump collects and dumps the free liquids from the inlet stream separately from the coalesced liquids.

A common specification of filter performance given by manufacturers is 100 percent removal of liquid droplets greater than 8 microns in diameter and 99.5 percent removal of particles in the 0.5-8 micron range. The removal efficiency for solid particles is commonly stated to be 99 percent for particles smaller than 10 microns. However, these numbers are difficult to determine in the field due to varying residence times and flow rates.

4.8 Potential Causes of Poor Separation of Entrained Liquids

Separator selection and sizing is always a trade off between cost and separation efficiency. If a separator is under-sized for the gas flow and/or liquid loading or operated outside the design capacity high liquids carry over will occur. This may be due to inadequate residence time for good gravity separation or due to re-entrainment of liquids in the mesh pad or vane separator (if present). Operating the separator with excessive level of collected liquids will also reduce the gas residence time and increase liquids carry over.

Also, if the separator is designed too short or the gas velocity is too high, liquids will be re-entrained into the gas stream, resulting in poor separation efficiency. An exhaustive search of available data gave no indication of oil field measurements of separator performance, so it is undetermined how efficiently liquid hydrocarbons can be removed from solution gas. However, Busch Martec in Pennsylvania claims their liquid hydrocarbon separators can operate with up to 99.5% efficiency.

Solution gas separators which only use gravity separation (no mesh pad or vane separator) will do a poor job of recovering liquid droplets smaller than 150 um. In separators with mist

extractors, the mesh, vane, centrifuge or filter must be firmly positioned in the vessel. Sudden surges of gas or fouling of the extractor may cause it to become dislodged. Gas bypassing the mesh pad will contain high levels of entrained liquids. If a mesh or vane separator is not installed on the exit of a gravity separator, generally droplets smaller than 150 um will remain entrained in the gas flow.

The separator must be sized for the expected amount of liquids passing through the vessel. If the vessel does not have enough liquid capacity, the mist extractor (if used) may become submerged and lose its effectiveness. Creating a larger vessel, limiting the flow of the inlet stream, or increasing the purge capacity may solve this problem.

Gas-liquid separators, including mesh pads and coalescing filters, will only remove liquid droplets. Light oils present in the vapour phase at the exit of the separator will condense out to form entrained liquids if the flare gas drops in temperature between the separator outlet and the flare tip. This cooling and condensation may be a significant source of entrained liquids, even at a site with efficient separation equipment installed. Any heat applied to the separator to reduce foaming or increase the rate of solid, oil, water and gas separation will vaporise the light oils. These oils may then condense prior to reaching the flare.

4.9 Solution Gas Survey

The results of the solution gas survey from the AEUB database show that the solution gas flow rate of 77% of the wells fall between 100 x 10^3 m^3/yr and 10000 x 10^3 m^3/yr. Ian Dowsett of the AEUB claimed that 7% of the solution gas being produced in Alberta is flared. Assuming this value of 7%, between 7000 m^3 and 700000 m^3 of solution gas at each site is being flared every year. Most solution gas contains entrained liquid hydrocarbons that, when burned, produce hazardous emissions that pollute the atmosphere. Liquid hydrocarbons are saleable, so if an efficient separation scheme can be developed to recover these hydrocarbons, the environment and the companies operating the wells can benefit.

4.10 Measured Performance of Solution Gas Separators as Installed in the Field

No data could be found in a search of the public literature that gave direct measurement of the performance of typical gas-oil separators installed at solution gas flares. Smith (1987) gives an "industry accepted" estimate of the oil content of gas exiting on oil and gas separator equipped with mist eliminators as ranging from 14.1 litres/m^3x10^6 to 141 litre/m^3x10^6. No field measurements of actual performance of a typical oil and gas separator could be found. This is a critical shortage of information considering the important effect of entrained liquids on increased flare emissions.

Experimental data is available from other industries. Fewel et al. (1997) report results of measurement of entrained liquids droplet size and concentration downstream of an in-line vane separator installed at a petrochemical plant. The separator was used to remove water droplets from a gas stream prior to entering a mole sieve dryer. In their testing, an isokinetic sampling system was used to measure the mass concentration of entrained liquids and a laser scattering probe was used to measure droplet size distribution. These measurements demonstrated the improved separation achieved by installing a coalescing filter after the vane separator.

5.0 COMPUTATIONAL TOOLS FOR ASSESSING THE EFFICIENCY OF SEPARATION TECHNOLOGIES

5.1 Background

Computational fluid dynamics (CFD) is a unique capability of the Environmental Technologies business unit. CFD, the simulation of fluid flows on the computer, has recently developed into a powerful and useful engineering tool. Historically CFD has been primarily applied in the aerospace industry. However, CFD is now being used to analyze and improve a wide range of fluids handling equipment from relatively simple duct flows and pumps to complex gas turbines to biomechanical systems such as blood vessels and heart valves.

A commercial CFD package called CFX-Tascflow, marketed and developed by AEA Technology Advanced Scientific Computing Ltd. of Waterloo, Ontario is used at the ARC. This is a very

comprehensive package that is suitable for most possible flow simulations. This software has a powerful grid generator to accurately simulate complex geometries. It is based on a multi-grid and multi-block solver that can handle the fully three-dimensional and turbulent Navier-Stokes equations. The software uses a finite volume representation with strict conservation of mass, momentum and turbulence to provide solutions to real engineering viscous flows. It also includes a Lagrangian particle tracking feature that can be used to simulate particle or droplet laden flows.

The computer modeling of fluid flows using CFD assists in reducing technology development costs by;

- analysis of existing equipment to guide incremental or retro-fit design improvements,
- simulation of design or process options that are outside the normal operating range of existing equipment,
- reduction of the number of experiments or tests required to develop new designs,
- reduction of design cycle time from concept to new product/process.

5.2 Limitations of CFD

While CFD is a powerful and increasingly used tool for engineering analysis it is important to realize that CFD results are an approximate simulation of a real flow. The simulation results are only as accurate as the assumptions and sub-models used to describe the physical phenomena being modeled. Some of the potential limitations of CFD, with respect to separator modeling, could include;

- turbulence models for highly swirling flow are complex,
- accurate models for very small drops or particles (Brownian diffusion) may be lacking,
- for accurate Lagrangian particle tracking results large numbers of particles may be required which greatly increases computer resource requirements (particle tracking can account for over 80% of the CPU time required to reach a converged solution)
- for non-disperse multi-phase flow accurate models may not be available,
- particle interaction effects (collision, breakup and coalescence) are not well understood,
- accurate inflow boundary data may not be available and model predictions are only as good as the assumptions that they were based on,
- modeling of unsteady or transient effects is difficult,
- even with advances in economical computer hardware performance, very large grids or complex geometries may make CFD impractical in terms of computer resource and time requirements

It is important to consider these, and other factors that may affect the accuracy of the CFD simulation results, before performing and when interpreting the output from CFD analyses.

5.3 Documented Application of CFD to Separator Design

The application of CFD to the design and understanding of flows in various types of separators is not new. There are numerous examples in the literature of the use of CFD in the evaluation of essentially all current separation devices relevant to oil field applications. What follows is a brief summary of some of the more recent applications of CFD to the analysis of separation equipment.

Fewel and Kean (1992) provide an excellent overview of how CFD can be of significant benefit to the improvement of separation technologies. They provide examples of the application of CFD to all common types of liquid/gas separation equipment. These include gravity separators, mesh pads, centrifugal separators (including cyclones), vane type (impingement) separators and combinations of these for specific applications. They demonstrate how CFD can be used to visualise and understand the details of the flow internal to the specific device and how this understanding can be used by the engineer to improve separation efficiency, pressure drop and capacity of various design or retro-fit situations. The authors give a brief overview of CFD theory and describe how models can be incorporated into the CFD software to deal with fibre filters, packings, and vane separation devices, as well as, handling the two-phase aspects of the flow. CFD is described as a powerful and useful procedure for the scale-up of prototype designs but emphasis is also placed on the use of this tool in conjunction with traditional experimental and empirical scaling techniques. The authors also stress need for accurate boundary condition data or assumptions to make the CFD analysis valid. For separation equipment this includes accurate gas flow rates and temperatures, droplet loading and size distributions at the separator inlet. These values should be based on actual data collected from the process stream on which the separator will operate whenever possible. The paper then describes in detail an example where CFD was used to develop a retro-fit design solution to a horizontal gas scrubber/separator that was only operating at 50% of original design capacity. The retro-fit design used a combination of mesh and vane separators and the performance test demonstrated full gas capacity of 500 MMscfd, as predicted by the CFD model.

Hallanger et. al. (1996) described the use of CFD to develop a model for a three-phase gravity separator. The model was applied to a first stage separator of a vertical inlet design with internal baffles operating in the Norwegian Oseberg field. Actual field measured data of water entrainment at varying interface levels in the vessel were available. The agreement between CFD and measured results was good. A very strong dependence of entrainment on droplet size was shown, as expected and overall separator performance was most dependent on the efficiency of the demister.

Madsen, et al. (1994) performed a very thorough analysis of the CFD predictions of the performance of gas cyclones. They performed a wide range of simulations on cyclones where extensive experimental data was available for comparison with the CFD results. They demonstrate that CFD analysis, if performed properly, can very accurately predict the performance of gas cyclones, with the exception of cases where 3D effects at the cyclone inlet are significant. The authors then demonstrate how the CFD model can then be used to relatively quickly investigate the effects of off-design operation (high or lower flow), different flow configurations (bottom flow), changing geometry (shortened swirl finder), and high temperature, high pressure flows. When compared with empirical models in the literature for cyclone scaling and performance they found that the CFD predictions were much closer to the measured experimental data.

Motta et. al. (1997) described the use of CFD to simulate one and two-phase flow in several gas-liquid cylindrical cyclone(GLCC) separator configurations. This work was performed to gain a better understanding of flow behaviour within the GLCC. The single and two-phase simulations were in very good agreement with experimental velocity data. Preliminary results for void fraction predictions showed the correct trends but work is still on-going.

Gottschlich, et al. (1993) details the utility of CFD in optimising the design of various separation devices used in the cement industry. The examples given in this paper were for a cyclone and a rotor separator. The authors conclude that the use of CFD provides clear insight into the flow dynamics occurring in processes and machines. The use of CFD analyses can substantially reduce the time and effort required for a product development project. Advantages to purchasers

of products that have been developed using CFD include increased confidence in a more optimised design and reduced risk with new or prototype designs. The paper also discusses the advantages of CFD analyses in the scientific understanding the results of pilot-scale tests and subsequent design scale-up.

6.0 STRATEGY AND METHOD DEVELOPMENT FOR SUITABLE SEPARATION AND SURROGATE MEASUREMENT TECHNOLOGIES.

The importance of entrained liquids to flare performance, the lack of information on actual solution gas separator performance and the lack of tested methods for surrogate measurements of flare performance all emphasize the need for a field test program. The objectives of the following proposed program are to test available equipment that could be used for either improving liquid separation from solution gas, or for other measurements of combustion efficiency at a suitable field test facility (modified oilfield battery site). More specific objectives of this proposed program would focus on:

- determining the impact of entrained liquids on flare emissions and how improved liquids recovery can be used to improve the quality of flare emissions;
- testing and/or developing improved liquids recovery techniques when required; and
- testing and development of methods for industry to monitor flare performance, either directly or through surrogate methods.

The following projects are based on solution gas flares being the most numerous in Alberta and the largest source of flare emissions.

6.1 Field Scale Testing of Impact of Entrained Liquids on Flare Emissions/Combustion Efficiency

Previous laboratory and field tests determined that liquids entrained in the solution gas going to flare reduce flare combustion efficiency and increase pollutant emissions. A test program is proposed that would focus on establishing, if possible, the correlations of liquid content of fuels in both gaseous and aerosol forms to separator operating conditions. The effect of these liquids on the resultant flare efficiency and emissions would be measured. The majority of these tests would be performed at one selected site. Testing at other field sites could be performed to

confirm results. Field test sites would be selected based on input from both government and industry.

Major components of this task are:

Site selection – a solution gas flaring site with separation equipment typical of most of Alberta's solution gas flares would be selected for testing in consultation with industry and government.

Modifications to equipment will be made to allow:

- measurement of flare gas flow rate and temperature at the exit of the separator and/or near the burner tip;
- access ports for extractive probe equipment and/or in-line optical equipment to measure liquid droplet concentration and size distribution and collection of liquid sample for analysis (access preferable both after the separator and near the flare tip);
- gas sampling access port for flare gas composition measurement by GC;
- access for installation of additional separation equipment from suppliers to examine effectiveness of further liquids removal immediately prior to entering the flare stack; and
- access for flare probes to measure flare emissions.

Baseline measurements at typical flow rates and separator conditions.

Measurements over a range of separator operating conditions.

Measurements after high efficiency liquids removal.

The results will hopefully reveal a correlation between entrained liquid content (both gaseous and aerosol) and droplet size with flare efficiency/emissions. They will also establish baseline information for need/justification for improved separation techniques and whether entrained liquids measurement can be used as a surrogate for monitoring flare emissions.

6.2 Survey of Existing Liquids Separation Equipment

This project task will survey and quantify the "typical" separation equipment installed on solution gas flares in Alberta and, based on design data, the entrained liquids removal performance of this separation equipment. The results of the study may identify sites that could reduce their flare emissions by improving liquids recovery as a saleable product.

Major components of this project would include:

- industry survey of installed equipment, including type of separation technology, gas flows, rate of liquids recovery, and actual use of the equipment vs. designed use. This task will require willing industry partners.
- field site visits to confirm how equipment is installed and used in the field;
- if improvements in liquids separation and recovery are needed, based on equipment currently available on the market or suitable for adapting to oil field use, recommendations will be made.

At the completion of this task, the type and performance of equipment currently operated in the field for removing entrained liquids will be documented. This information will be used for quantifying the potential reduction in flare emissions through equipment upgrades or improved operation. Also any requirement for improved equipment design will be identified.

6.3 Identification and Testing of Methods for Monitoring Flare Performance

With the possible regulation of flare combustion efficiency and emissions, there will be a requirement for more cost-effective ways to measure flare emissions either directly or through surrogate measurements that correlate with flare emissions. Depending on cost and regulatory requirements, the measurement methods required may be continuous, on-line measurements or may be intermittent (e.g. yearly).

The tasks in this project will depend somewhat on results from Items 1 and 2 and also on pending requirements for monitoring flares. Major components of this project may include:

- survey of existing monitoring equipment, including remote monitoring, entrained liquids monitoring;
- identify key parameters that need to be measured based on information from the literature and results of Item 1 testing;
- identify instruments with potential for on-line measurement and/or intermittent measurement of flare emissions or surrogates; and
- set up identified instruments to test them in the field tests identified in Item 1.

When finished, this task will have identified and tested instruments suitable for monitoring flare performance and flare emissions to meet regulatory (or public pressure) requirements.

6.4 Improved Liquids Recovery Techniques

The need for doing this task will depend on the results of Item 1 and Item 2. If current installations have excessive entrained liquids in the flared gas and there is no current technology (such as mist eliminators) to remove these liquids in a practical manner (i.e. that people would use in the field), then a focused R&D program is required to design, improve and test better separation technologies. Other existing tools and capabilities that would help in this task include:

- computational fluid dynamics for flow and separation simulations of new designs or improvements to existing designs; and
- facilities for physical testing of new designs from laboratory scale up to field scale.

6.5 Avoidance of Flaring

The choice of solution gas flaring or solution gas recovery will be an economic decision. If technical issues prevent recovery of the gas a focused R&D program will be required to develop either new technologies or adapt existing technology.

7.0 CONCLUSIONS

The current study was conducted to survey best available technologies for use or development that would enable the upstream oil and gas industry to substantially reduce hydrocarbon emissions from flaring of solution gas at oilfield battery sites in Alberta. The study focussed on surrogate methods for measuring flare performance and on techniques for removal of entrained liquids from solution gas prior to flaring.

Measurement of flare performance by the present flame sampling and analysis technique is complex, time consuming, and expensive to conduct. Surrogate methods to indicate flare performance could include techniques to measure the flare gas flow rate and composition and/or techniques for remote monitoring of flare properties and/or emissions.

On-line measurement of flare gas flow rate, composition and content of entrained liquids may be a good surrogate measurement of relative flare performance. Entrained hydrocarbon liquids in the flare gas represent lost revenue, significantly decrease flare combustion efficiency and increase emissions of unburned hydrocarbons and soot. On-line measurement of the concentration of entrained liquids and preferably also the droplet size distribution would yield valuable data on solution gas separator performance and give an indication of potential high flare emissions. Although commercial instruments exist for measuring flare gas flow rate and gas composition, the measurement of entrained liquids in the gas requires gas sampling and liquid collection methods or expensive optical techniques. Neither method would be suitable for continuous on-line monitoring of entrained liquids.

Remote monitoring methods examined for assessing flare performance included both laser and infrared spectrometer systems. Many varieties of both systems have previously been evaluated for measurements of numerous sources of hydrocarbon emissions. These applications included fugitive emissions monitoring at various petroleum operations, hydrocarbon monitoring of reservoir leakage for use in petroleum exploration, and engine exhaust emissions measurements. A number of the systems examined have shown promise for their particular application. Others have provided disappointing results when accuracy comparisons were made to results obtained by conventional techniques such as gas chromatography. There has been one study related to the quantification of flare emissions using a remote measurement technique. A passive infrared system was used in this application which showed uncertainties in the spatial distributions of temperature and gas concentration, and in the detection of hydrocarbon species. Available instruments for remote monitoring require further testing and verification prior to acceptance as a surrogate method of monitoring.

Literature and Internet searches were used to examine techniques for the separation of liquid hydrocarbons from gasses. These searches focussed on available technologies currently used or that could be modified or developed for solution gas clean up. The gas-liquid separator designs available include gravity separators, cyclones, vane and mesh-type mist eliminators, coalescing filters and electrostatic precipitators. Currently the oil and gas industry primarily uses gravity separators that remove droplets larger than 150 um which may or may not be followed by vane

or mesh mist eliminators that remove droplets larger than 10 um. There was no measured data found in the literature on entrained liquids remaining in solution gas after typical oil-field separation equipment. Conditions which could lead to excessive entrained liquids going to flare include undersized separation equipment, gravity separators with no mist eliminator, and gas by-passing the mist eliminators. Also, light oils present in the vapour phase at the separator will not be recovered and may condense out between the separator outlet and the flare tip to form entrained liquids at the flare.

The application and utility of computational fluid dynamics (CFD) to the design and understanding of flows in various types of separators is well established. CFD has been used to evaluate essentially all current separation devices relevant to oil field applications. The use of CFD analyses can substantially reduce the time and effort required for a product development and evaluation.

Currently there is inadequate information on:

- separation equipment currently installed in Alberta to clean solution gas prior to flaring
- the amount and variability of entrained liquids going to flare at typical oilfield battery sites
- correlation between flare gas composition, entrained liquids content and flare performance
- instrumentation for on-line measurement of flare gas composition (including entrained liquids)
- instrumentation for remote monitoring of flare performance and emissions

A field test program is required to quantify this missing data so that correct decisions can be made on ways and means to improve solution gas flare performance and to monitor and reduce emissions. A solution gas-flaring site with separation equipment typical of most of Alberta's solution gas flares should be selected for testing in consultation with industry and government. Tests should include baseline measurements at typical flow rates and separator conditions, measurements over a range of separator operating conditions and measurements after high efficiency removal of liquids. The results would hopefully reveal a correlation between entrained liquid content (both gaseous and aerosol) and droplet size with flare efficiency/emissions and insight into methods for remote monitoring of flares.

8.0 RECOMMENDATIONS

The current study was conducted to survey best available technologies for use or development to substantially reduce hydrocarbon emissions from flaring of solution gas at oilfield battery sites in Alberta. The study focussed on surrogate methods for measuring flare performance and on techniques for removal of entrained liquids from solution gas prior to flaring. The following is recommended based on the results of this study.

1. Existing solution gas separation equipment should be surveyed to document the separation equipment installed, its operation and its estimated entrained liquids removal performance. The potential for improved flare performance by improved liquids recovery could then be identified.

2. A field test program is recommended to establish the amounts of entrained liquids in flared solution gas and, if possible, correlate entrained liquid content with flare performance and emissions.

3. At the completion of baseline separator and flare performance testing, further tests should examine the effect of improved liquids separation and recovery on flare performance and emissions. These tests should include measurement of entrained liquid content and droplet size distribution.

4. The field test site should also be used to test and/or develop methods for surrogate measurement of flare performance and emissions. Surrogates to be tested should include methods based on inlet gas composition, entrained liquids content and remote monitoring of the flare.

5. Further work is required to identify technology needs for increased utilization of solution gas in order to avoid the need for flaring.

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